The excitation of 5-min oscillations in the solar corona

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ABSTRACT

Aims. We aim to study excitation of the observed ∼ 5-min oscillations in the solar corona by localized pulses that are launched in the photosphere.
Methods. We solve the full set of nonlinear one-dimensional Euler equations numerically for the velocity pulse propagating in the solar atmosphere that is determined by the realistic temperature profile.
Results. Numerical simulations show that an initial velocity pulse quickly steepens into a leading shock, while the nonlinear wake in the chromosphere leads to the formation of consecutive pulses. The time interval between arrivals of two neighboring pulses to a detection point in the corona is approximately 5 min. Therefore, the consecutive pulses may result in the ∼ 5-min oscillations that are observed in the solar corona.
Conclusions. The ∼ 5-min oscillations observed in the solar corona can be explained in terms of consecutive shocks that result from impulsive triggers launched within the solar photosphere by granulation and/or reconnection.

Key words. Sun: atmosphere – Sun: oscillations

1. Introduction

Propagating acoustic waves are frequently seen in the solar corona as periodic variations of spectral line intensity (De Moortel et al. 2000, 2002, Marsh et al. 2003, Lin et al. 2005, 2006, Srivastava et al. 2008, Wang et al. 2009). As these waves are often observed within the frequency range corresponding to the acoustic waves in the solar photosphere/chromosphere, this logically leads to the idea of penetration of the photospheric acoustic oscillations into the corona. However, the photospheric 5-min oscillations are evanescent in the gravitationally stratified solar atmosphere as their frequency is lower than the cut-off frequency (Lamb 1908, Roberts 2004, Musielak et al. 2006). Bel & Leroy (1977) suggested that the cut-off frequency of the magnetic field-free atmosphere is lower for waves propagating obliquely to the vertical direction. De Pontieu et al. (2005) proposed that p-modes may be channeled into the solar corona along inclined magnetic field lines as a result of the decrease of the acoustic cut-off frequency. McIntosh & Jefferies (2006) found the observational justification of the modification of the cut-off frequency by inclined magnetic field. As the magnetic field of active region loops is predominantly vertical in the photosphere/chromosphere, it is unclear how p-modes may penetrate into the coronal regions.

There are two different types of drivers in the highly dynamic solar photosphere: oscillatory (e.g. p-modes) and impulsive (e.g. granulation and/or explosive events due to magnetic reconnection). Both types of drivers may be responsible for the observed dynamical phenomena in upper atmospheric regions.

As a result of the rapid decrease of mass density with height, finite-amplitude high-frequency photospheric oscillations can quickly grow in their amplitudes and steepen into shocks, which by energy dissipation can lead to the chromospheric heating (Narain & Ulmschneider 1990, 1996, Carlsson & Stein 1997, Ruderman 2006). Lower-frequency waves, those with ∼5 min period, are not good candidates for the chromospheric heating (Narain & Ulmschneider 1990).

It was found by Hollweg (1982) that a localized pulse that is launched initially sets up a nonlinear wake which results in a trail of consecutive shocks. Such shocks were called rebound shocks by Hollweg (1982).

The time interval between consecutive shocks is close to the period of the nonlinear wake. In the linear case, the wake oscillates with the acoustic cut-off frequency of the stratified atmosphere. Nonlinearity modifies the wave period of the wake, with many features of spicules which exhibit the periodicity of about 5-min (Murawski & Zaqarashvili 2010). Then, these quasi-periodic shocks may lead to the oscillatory dynamics of coronal plasma, which is observed as intensity oscillations in coronal spectral lines.

The aim of this paper is to study the role of rebound shocks, which are formed by an impulsive perturbation, on the observed ∼ 5-min oscillations in the solar corona. Here we consider the simplest hydrodynamic case, which can be

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developed to more realistic magnetohydrodynamic model in future studies.

This paper is organized as follows. The basic equations and the atmospheric model are described in Sect. 2. The numerical model and results of numerical simulations of impulsive photospheric driver are discussed in Sect. 3. This paper is concluded by a summary of the main results in Sect. 4.

2. Basic model

2.1. Hydrodynamic equations

Our model system is taken to be composed of a gravitationally-stratified solar atmosphere that is described by one-dimensional (1D) Euler equations:

$$\frac{\partial \varrho}{\partial t} + \frac{\partial (\varrho V)}{\partial y} = 0 \,, \tag{1}$$

$$\varrho \frac{\partial V}{\partial t} + \varrho V \frac{\partial V}{\partial y} = -\frac{\partial p}{\partial y} - \varrho g \,, \tag{2}$$

$$\frac{\partial p}{\partial t} + \frac{\partial (pV)}{\partial y} = (1 - \gamma)p \frac{\partial V}{\partial y} \,. \tag{3}$$

Here ϱ denotes the mass density, V is a vertical component of the flow velocity, $p = k_B \varrho T/m$ is the gas pressure, $\gamma = 5/3$ is the adiabatic index, $g = 272$ m s^{-2} is the gravitational acceleration, T is the temperature, m is the mean particle mass and k_B is Boltzmann's constant.

2.2. The equilibrium

We assume that at the equilibrium the solar atmosphere is settled in a static ($V = 0$) environment in which the pressure gradient force is balanced by the gravity, that is

$$-\frac{\partial p_0}{\partial y} - \varrho_0 g = 0 \,. \tag{4}$$

With the use of the equation of state we obtain the equilibrium gas pressure and mass density as

$$p_0(y) = p_{00} \, \exp\left(-\int_{y_r}^y \frac{dy'}{\Lambda(y')}\right), \quad \varrho_0(y) = \frac{p_0(y)}{g\Lambda(y)} \,. \tag{5}$$

Here $\Lambda(y) = k_B T(y)/(mg)$ is the pressure scale-height and p_{00} is the gas pressure at the reference level, chosen here at $y_r = 10$ Mm.

We adopt a realistic temperature profile $T(y)$ for the solar atmosphere (Vernazza et al. 1981). In this profile T attains a value of about 5700 K at the top of the photosphere which corresponds to $y = 0.5$ Mm. At higher altitudes $T(y)$ falls off until it reaches its minimum of 4350 K at $y \simeq 0.95$ Mm. Higher up $T(y)$ grows gradually with height up to the transition region which is located at $y \simeq 2.7$ Mm. Here $T(y)$ experiences a sudden growth up to the coronal value of 1.5 MK at $y = 10$ Mm. Having specified $T(y)$ we can obtain mass density and gas pressure profiles with the use of Eq. (5).

Equations (1)-(3) are to be solved numerically for an impulsive perturbation launched initially within the solar photosphere. The numerical simulations for a harmonic driver were already reported elsewhere (e.g. Erdélyi et al. 2007, Fedun et al. 2009 and references therein). Therefore, it is justifiable to limit our study to the case of impulsively generated waves.

2.3. Linear approximation

Neglecting all nonlinear terms in Eqs. (1)-(3) leads to the classical Klein-Gordon equation (Rae and Roberts 1982, Roberts 2004)

$$\frac{\partial^2 Q}{\partial t^2} - c_s^2 \frac{\partial^2 Q}{\partial y^2} + \Omega_c^2 Q = 0, \tag{6}$$

where $Q(t,y) = V(t,y)\sqrt{\varrho_0(0)c_s^2(0)/\varrho_0(y)c_s^2(y)}$ and

$$\Omega_c^2(y) = \frac{c_s^2}{4\Lambda}\left(1 + 2\frac{\partial \Lambda}{\partial y}\right). \tag{7}$$

In the case of an isothermal atmosphere, the Klein-Gordon equation implements a natural frequency of the stratified medium, $\Omega_c = c_s/2\Lambda$, called the cut-off frequency for acoustic waves. A physical interpretation of the cut-off frequency is that waves of lower (higher) frequencies than Ω_c are evanescent (propagating). According to the theory developed for the linear Klein-Gordon equation the initially launched pulse results in a leading pulse which propagates with the sound speed. This pulse is followed by the wake, which oscillates with Ω_c and gradually decays as time progresses (Lamb 1908, Rae and Roberts 1982). However, situation is changed when one considers nonlinear terms in Eqs. (1)-(3). Then, a large-amplitude initial pulse may lead to consecutive shocks due to nonlinearity (Hollweg 1982). In the nonlinear regime, the wake may oscillate with the period, which differs from the linear cut-off period. Then the interval between consecutive shocks may depend on the amplitude of the initial pulse (Murawski and Zaqarashvili 2010). We solve the fully nonlinear equations for a realistic atmospheric model numerically and the results are presented in the next section.

3. Numerical simulations for impulsively generated waves

Equations (1)-(3) are solved with a use of the code FLASH (Dubey et al. 2009). We set the simulation region as -0.5 Mm $\leq y \leq 29.5$ Mm and at the numerical boundaries we fix in time all plasma quantities to their equilibrium values. In our studies we use an adaptive mesh refinement (AMR) grid with a minimum (maximum) level of refinement blocks set to 3 (9). In the simulations, we excite waves by launching at $t = 0$ s the initial velocity pulse of a Gaussian profile

$$V(y, t=0) = A_v \exp\left[-\frac{(y-y_0)^2}{w^2}\right] \tag{8}$$

with A_v the amplitude of the initial pulse, y_0 its initial position and w its width. We set and hold fixed $y_0 = 0.5$ Mm and $w = 0.1$ Mm, but allow A_v to vary in different simulations.

At the initial stage of the wave evolution the initial pulse splits into counter-propagating waves. As a result of the rapid decrease of the equilibrium mass density, the upward propagating pulse grows in its amplitude and quickly steepens into a shock. Figure 1 illustrates the spatial profile of $V(y)$ at $t = 250$ s for $A_v = 1$ km s^{-1}. At this time, the pulse reaches the level $y = 23.5$ Mm, while the secondary shock begins to form from the nonlinear wake at $y = 2$ Mm. Later on, this secondary shock propagates upwards, and then it

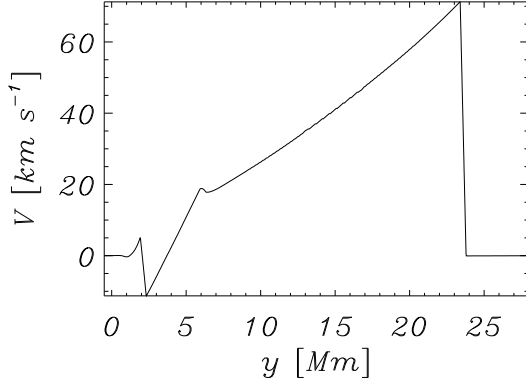**Fig. 1.** Velocity (in units of 1 km s^{-1}) profile vs height y (in units of 1 Mm) at $t = 250$ s for $A_\mathrm{v} = 1$ km s^{-1}. Here $y = 0$ Mm ($y \simeq 2.7$ Mm) corresponds to the base of the photosphere (the transition region).

is followed by the next shock. This process repeats in time until the perturbation energy finally subsides to zero.

Figure 2 displays the temporal dynamics of the velocity that is collected at $y = 20$ Mm for the initial pulse amplitude of $A_\mathrm{v} = 1$ km s^{-1} (top panel) and $A_\mathrm{v} = 2$ km s^{-1} (bottom panel). In the top panel, the arrival of the leading shock to the detection point occurs at $t \simeq 250$ s and the second pulse reaches the detection point at $t \simeq 570$ s i.e. after ~ 320 s. Thus, the nonlinear wake in the chromosphere excites quasi-periodic upward propagating pulses, which enter the corona and may cause quasi-periodic intensity oscillations which are observed in the imaging data. For $A_\mathrm{v} = 1$ km s^{-1}, which is close to the typical granular velocity, the interval between arrivals of neighboring shocks is near 5-min (Fig. 2, top). This means that the nonlinear wake in the realistic atmosphere and for the initial perturbations, corresponding to the solar granular velocity, exhibits about a 5-min wave period, i.e. it is longer than in the linear isothermal case (~ 3-min in the chromosphere). Time-signature for $A_\mathrm{v} = 2$ km s^{-1} shows that the leading shock arrives to the detection point at $t \simeq 190$ s, while the second shock reaches this point at $t \simeq 630$ s, i.e. after ~ 440 s (Fig. 2, bottom panel). It is clearly seen that the interval between arrival times of two consecutive shocks is longer for a larger amplitude of the initial pulse.

4. Discussion and summary

Frequently observed ~ 5-min oscillations in the solar corona are often explained by leakage of photospheric p-modes along inclined magnetic field. Vertically propagating acoustic waves with 5-min period are evanescent due to the stratification of the solar atmosphere as chromospheric acoustic cut-off period is ~ 3 min (Roberts 2004). But, acoustic-gravity waves have a smaller cut-off frequency when they propagate with the angle about the vertical. This may allow the photospheric 5-min oscillations to channel along a stratified chromosphere and penetrate into the corona (De Pontieu et al. 2005, Erdélyi et al. 2007, Fedun et al. 2009). In order to increase the cut-off period from 3-min up to 5-min, the propagation angle (or magnetic field inclination)
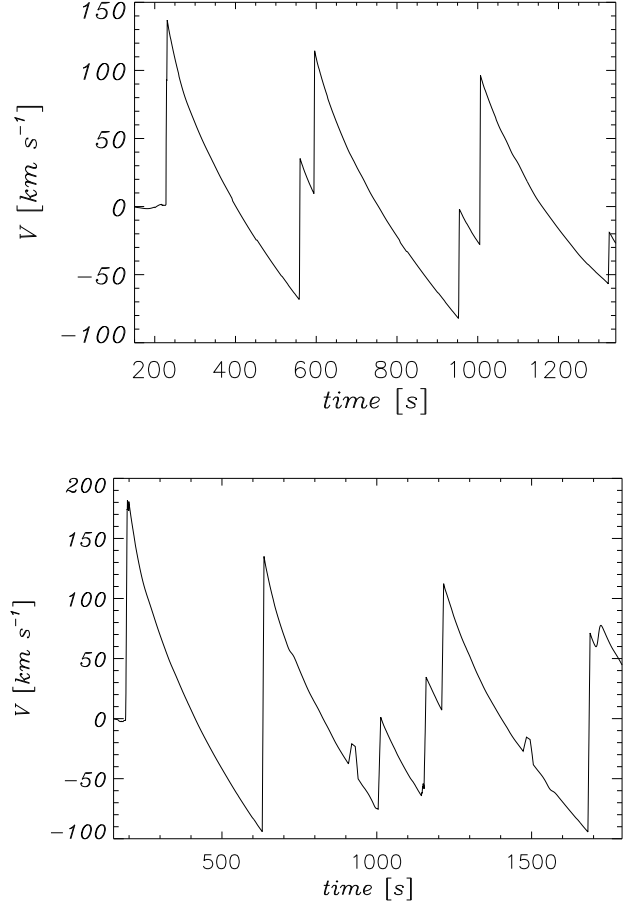

Fig. 2. Time-signatures of V (in units of km s^{-1}) collected at $y = 20$ Mm for the case of $A_\mathrm{v} = 1$ km s^{-1} (top panel) and $A_\mathrm{v} = 2$ km s^{-1} (bottom panel). Time is expressed in units of 1 s.

should be $\theta \sim 50^0$ ($\cos\theta \approx 3/5$). Therefore, the leakage of p-modes may take place only in particular regions of the solar atmosphere, where the magnetic field is significantly inclined in the chromosphere.

In this paper, we suggest an alternative mechanism to explain the observed oscillations in the solar corona, which is based on the rebound shock model of Hollweg (1982). We numerically solved the full set of Euler equations for the realistic VAL-C temperature profile and for a Gaussian velocity pulse launched within the photosphere. We found that velocity pulses, originating from granules or magnetic reconnection in the lower regions, lead to different responses of the chromosphere/transition region than the periodic acoustic waves resulting from p-modes. It must be mentioned, that the energy of granular motions is higher than the energy of p-modes, therefore the impulsively triggered waves should have more power than those triggered by a periodic driver.

The numerical simulations show that as a result of the rapid decrease of the equilibrium mass density the initial velocity pulse quickly steepens into a shock. The shock propagates into the corona, while the nonlinear wake is formed in the chromosphere due to the atmospheric stratification. This nonlinear wake leads to consecutive shocks as was first

shown by Hollweg (1982). The interval between the arrival times of two consecutive shocks depends on the amplitude of the initial pulse; a stronger pulse leads to longer intervals. The initial pulse with the granular velocity of 1 km s^{-1} leads to ~ 5-min intervals between consecutive shocks. Therefore, the quasi-periodic arrival of consecutive shocks in the solar corona may cause the intensity oscillations with a period close to the interval between the shocks.

We implemented a simple 1D analytical model in order to avoid the propagation of acoustic oscillations with the angle to the vertical. We showed that purely vertically propagating pulses may lead to quasi 5-min oscillations in the corona due to consecutive shocks. Therefore, it is not necessary to invoke the propagation along inclined magnetic field in order to explain the observed 5-min periodicity in the corona.

One dimensional propagation for acoustic waves is justified for purely vertical magnetic field. In this case, acoustic waves are in fact slow magneto-acoustic waves for low plasma $\beta \sim c_s^2/v_A^2 < 1$ and fast magneto-acoustic waves for high plasma $\beta > 1$. Here v_A is the Alfvén speed. In the solar photosphere β is larger than unity, but it rapidly decreases due to the mass density fall off with height (and consequent increase of the Alfvén speed). It becomes smaller than unity in the chromosphere (Gary 2001) and tends to unity somewhere between the photosphere and the chromosphere and this surface should be thinner than the width of the chromosphere. The linear fast and slow magneto-acoustic waves are coupled near the level of $\beta \sim 1$ when they propagate obliquely to the magnetic field (Rosenthal et al. 2002, Bogdan et al. 2003). However, these waves remain purely acoustic for parallel propagation unless the tube dispersive effects are taken into account. Therefore, a pulse propagating along the vertical magnetic field may not feel the $\beta \sim 1$ surface. On the other hand, the acoustic wake, which is formed behind the pulse and oscillates along the magnetic field, may lead to the non-linear energy transfer into Alfvén waves near the $\beta \sim 1$ region (Zaqarashvili and Roberts 2006, Kuridze and Zaqarashvili 2008). This effect may be revealed as far as one includes the magnetic field into numerical simulations. Then, a part of oscillation energy may be transformed into transverse oscillations near this region, but most of energy will remain in longitudinal oscillations due to thinness of $\beta \sim 1$ region. Therefore, $\beta \sim 1$ region may not significantly affect the formation of rebound shocks in the chromosphere and consequently quasi-periodic acoustic oscillations in the lower corona. However, a two-dimensional consideration and inclusion of magnetic field are necessary for the complete understanding of the proposed scenario. The first step in this direction was already done by Murawski and Zaqarashvili (2010) in the modeling of spicule formation, but they considered a simple temperature profile covering only the chromosphere-corona. The plasma β was considered less than unity along the whole simulation region, therefore the effects of the $\beta \sim 1$ region were absent in these simulations. We intend to consider the rebound shock model in the case of magnetic field and realistic temperature profile in the future.

An important consequence of the rebound shock model is that the interval between consecutive shocks depends on the initial amplitude of pulse (see Fig. 2). The smaller amplitude pulses lead to shorter interval between consecutive shocks with lower limit of 3-min, which is the linear acoustic cut-off period of the solar atmosphere. The interval is longer for stronger initial pulses being ~ 5-min for 1 km s^{-1} in the photosphere. Then the rebound shock model predicts the longer period oscillations above the regions of strong granular power. The granulation is suppressed in strong magnetic field regions of the photosphere (e.g. sunspots), therefore the initial pulses should have smaller amplitudes there, leading to the oscillation at near cut-off frequency. Indeed, the strong magnetic field regions (sunspots, magnetic network cores) show predominantly 3-min oscillations in the chromosphere. Note that some observations also show the 3-min oscillations in the solar corona above sunspots (De Moortel et al. 2002) and other magnetic structures (Lin et al. 2005). These oscillations can be excited as a consequence of consecutive shocks due to chromospheric 3-min oscillations.

As a result, we expect that ~ 5-min oscillations can be detected above the regions where the granular energy is significant i.e. the quiet Sun and surroundings of active regions/magnetic network. This is consistent with observations. On the other hand, the detection of 5-min oscillations in the quiet corona is not an easy task due to a relatively weak intensity of coronal lines. However, a careful analysis still can be performed. But, one should keep in mind that the dynamics of acoustic waves in the field-free regions and along the vertical magnetic field could be quite different as it was discussed above. An initial acoustic pulse may be spread horizontally in field-free regions, while almost the whole energy would be guided along the field lines in magnetic structures. Therefore, the amplitude of intensity oscillations could be smaller in the quiet corona than near active regions and chromospheric network cores. However, the divergence of magnetic field and increased thermal conduction may significantly weaken the amplitude of coronal oscillations, which seem to be quite strong and non-linear on Figs. 1 and 2. Then, the strong slow wave pulses may become almost linear once they penetrate into the corona as it is seen by observations. Our numerical model then requires the inclusion of magnetic field and the thermal conduction (at least, in the coronal part of the atmosphere). This will be done in future studies.

It should be noted that the granular velocities may take values between 0.5-2 km s^{-1} with peak on 1 km s^{-1}. As the interval between consecutive shocks strongly depends on the amplitude of the initial pulse, then the resulted coronal oscillations may take values between 4-7 min with a peak on 5-min. Indeed, the wavelet analysis of coronal line images obtained by Hinode/EIS show that the oscillation power of coronal oscillations is concentrated at the period in a range of 4-6 min (Wang et al. 2009), which is fully consistent with our theory.

Our simulations were performed for an isolated pulse in order to show clearly the effect of rebound shocks. However, the solar photosphere is very dynamic, hence the initial pulse probably is followed by other pulses. The subsequent pulse coming from the photosphere may also trigger the consecutive shocks in the chromosphere. The interaction between rebound shocks formed by different photospheric pulses may set up complex dynamics in the chromospheric plasma with immediate influence on the lower corona. Therefore, the coronal oscillations may have broad spectrum as we already discussed in the previous paragraph. On the other hand, if the mean interval between subsequent initial pulses is close to the mean interval be-

tween consecutive shocks, then a resonance may occur in the chromosphere. This could be subject of future study.

The excitation of coronal oscillations due to leakage of p-modes may occur only along significantly inclined magnetic field in the chromosphere (in order to reduce the cut-off frequency). The magnetic field lines, which are significantly inclined from the vertical in the chromosphere, may not reach the corona at all. Therefore, the p-mode leakage may have problems in real geometry of active region magnetic field. On the contrary, the rebound shock mechanism may work in any geometry of magnetic field including the purely vertical field lines. Therefore, the excitation of 5-min oscillations in the solar corona by photospheric impulsive drivers has larger area of application than that of by p-modes. We believe that the future sophisticated models may shed light on the excitation of coronal acoustic waves.

Our conclusions are:

(a) a velocity pulse that is initially launched at the photospheric level (due to granules or reconnection) quickly steepens into a shock and can penetrate into the corona, while a nonlinear wake that is formed behind this shock leads to consecutive shocks in the chromosphere;

(b) for the initial photospheric pulse amplitude of $1\ \mathrm{km\ s^{-1}}$ the time interval between two consecutive shocks is ~ 5-min; the consecutive shocks propagate upwards and may cause the observed 5-min intensity oscillations in the solar corona;

(c) the final conclusion is that the observed ~ 5-min oscillations in the solar corona could be caused by impulsive photospheric perturbations (convection, reconnection) not necessarily by p-modes.

References

Bel, N., Leroy, B., 1977, A&A, 55, 239

Bogdan, T.J., Hansteen, M., Carlsson, V., et al. 2003, ApJ, 599, 626

Carlsson, M., Stein, R.F., 1997, ApJ, 481, 500

De Moortel, I., Ireland, J., Walsh, R.W., 2000, A&A, 355, L23

De Moortel, I., Ireland, J., Hood, A.W., Walsh, R.W., 2002, A&A, 387, L13

De Pontieu, B., Erdélyi, R., De Moortel, I., 2005, ApJ, 624, L61

Dubey, A., Antypas, K., Ganapathy, M.K., Reid, L.B., 2009, Riley, K., Sheeler, D., Siegel, A., Weide, K., Extensible component-based architecture for FLASH, a massively parallel, multiphysics simulation code, Parallel Computing, 35, Issues 10-11, October-November 2009

Erdélyi, R., Malins, C., Tóth, G., de Pontieu, B., 2007, A&A, 467, 1299

Fedun, V., Erdélyi, R., Shelyag, S., 2009, Solar Phys., 258, 219

Hollweg, J.V., 1982, ApJ, 257, 345

Gary, G.A., 2001, Solar Phys., 203, 71

Kuridze, D., Zaqarashvili, T.V., 2008, J. Atmos. Solar-Terres. Phys., 70, 351

Kuridze, D., Zaqarashvili, T.V., Shergelashvili, B.M., Poedts,S., 2009, A&A, 505, 763

Lamb, H., 1908, Proc. London Math. Soc, 1908, 7, 122

Lin C.H., Banerjee, D., Doyle, J.G., O'Shea E., 2005, A&A, 444, 585

Lin C.H., Banerjee, D., O'Shea E., Doyle, J.G., 2006, A&A, 460, 597

Marsh, M.S., Walsh, R.W., De Moortel, I., Ireland, J., 2003, A&A, 404, L37

McIntosh, S.W., Jefferies, S.W., 2006, ApJ, 647, L77

Murawski, K., Zaqarashvili, T., 2010, A&A, 519, A8

Musielak, Z.E., Musielak, D.E., Mobashi, H., 2006, Phys. Rev. E, 036612

Narain, U., Ulmschneider, P., 1990, Space Sci. Rev., 54, 377

Narain, U., Ulmschneider, P., 1996, Space Sci. Rev., 75, 453

Rae, I.C., Roberts, B., 2002, ApJ, 256, 761

Roberts, B., 2004, In Proc. SOHO 13 Waves, Oscillations and Small-Scale Transient Events in the Solar Atmosphere: A Joint View from SOHO and TRACE, Palma de Mallorca, Spain, (ESA SP-547), 1

Rosenthal, C.S., Bogdan, T.J., Carlsson, M., et al. 2002, ApJ, 564, 508

Ruderman M.S., 2006, Phyl. Trans, R. Soc. A, 364, 485

Srivastava, A.K., Kuridze, D., Zaqarashvili, T.V., Dwivedi, B.N., 2008, A&A, 481, L95

Vernazza, J.E., Avrett, E.H., Loeser, R., 1981, ApJ, 45, 635

Wang, T.J., Ofman, L., Davila, J.M., 2009, ApJ, 696, 1448

Zaqarashvili, T.V., Roberts, B., 2006, A&A 452, 1053